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14. ABSTRACT
The sensitivity of magnetoelectric (ME) sensors is more than an order of magnitude higher at their mechanical resonant frequency fr. By applying a restoring torque to an asymmetric ME sensor, we have increased its effective stiffness and, thus, fr by 20% while maintaining the enhanced sensitivity at resonance. The torque was dependent on both the tensile force from a suspended weight and the length of the wire attaching it. This provides two alternative routes for tuning fr to

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Enhanced sensitivity of magnetoelectric sensors by tuning the resonant frequency

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REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

Continuation for Block 13

ARO Report Number 52866.34-MS
Enhanced sensitivity of magnetoelectric sensors ...

Block 13: Supplementary Note

Enhanced sensitivity of magnetoelectric sensors by tuning the resonant frequency

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The sensitivity of magnetoelectric (ME) sensors is more than an order of magnitude higher at their mechanical resonant frequency f_r. By applying a restoring torque to an asymmetric ME sensor, we have increased its effective stiffness and, thus, f_r by 20% while maintaining the enhanced sensitivity at resonance. The torque was dependent on both the tensile force from a suspended weight and the length of the wire attaching it. This provides two alternative routes for tuning f_r to optimize performance. We have detected fields below 10 pT at both the shifted and unshifted f_r of 132.2 Hz. © *2011 American Institute of Physics*. [doi:10.1063/1.3617428]

There has been considerable recent progress in magnetic sensor technology. This progress has included a chip scale atomic magnetometer,[1] a method[2,3] for mitigating the effect of 1/*f* noise, magnetic tunnel junctions[4,5] with magnetoresistance ratios of hundreds of percent, and magnetoelectric (ME) sensors,[6] which generate an output voltage or charge without requiring any operating power. ME sensors consist of layers or plates of at least two components, a magnetostrictive layer, such as Metglas, and a piezoelectric layer, such as lead zirconate titanate (PZT). These plates or laminates are mechanically coupled by nonconductive epoxy. The presence of a magnetic field causes the magnetostrictive material to stress the piezoelectric material, which then generates a charge. ME laminates can passively detect low-frequency, pT magnetic fields.[6] The geometry of the layers in a ME sensor may be symmetric (e.g., Metglas-PZT-Metglas trilayer) or asymmetric (e.g., Metglas-PZT bilayer) about a central plane parallel to the layers. The ME response (as measured by the voltage coefficient α_{ME} in terms of V/cm Oe) of both the symmetric[6] and asymmetric[7] ME sensors is increased by approximately a factor of 10 at their mechanical resonant modes f_r. The major normal mode of the symmetric ME sensor is a compressional, longitudinal mode along its length; it is known as the L-T mode when the piezoelectric component is poled transverse to the longitudinal magnetic measurement direction. This mode usually has a resonant frequency f_r above a kilohertz. When one end is fixed in a cantilever configuration, the asymmetric ME sensor has a several hundred Hz bending mode. A theoretical discussion of the operation of asymmetric ME sensors is given elsewhere.[7]

To take advantage of the increased response at resonance for sensor applications and the growing energy harvesting field, it is desirable to tune the resonant frequency to match an input frequency that may vary in time.[8] Previously, it was established that one could shift the resonant frequency of asymmetric ME sensors by using axial preloads,[9] magnetic fields,[10,11] or by adding a mass to the cantilever tip.[12] Here, we report on what can be an *in situ* method of increasing the resonant frequency f_r in ME sensors and similar mechanical devices while maintaining the increased sensitivity of better than 10 pT at f_r. This sensitivity is comparable to that of expensive optically pumped magnetometers.[13] The increase in f_r is achieved by applying an in-plane tensile force via a suspended weight. In a commercial device, one can replace the weight with a piezoelectric actuator. The method allows the tuning of the resonant frequency of mechanical devices to match a signal whose dominant frequency changes in time.

Our experiments demonstrating this approach were performed on self-biased, asymmetric, cantilever ME sensors that were 6 cm × 1 cm × 0.5 cm laminates consisting of three layers of 25-μm Metglas/200-μm Ni/300-μm PZT, all mechanically coupled with epoxy. Electrical leads were silver-epoxied to the PZT, which was poled transverse to the length of the laminate in an L-T configuration. The Ni provided the necessary field to bias each ME sensor. Recent investigations[14,15] of asymmetric sensors in which the ferromagnetic layer is composed of two phases with different magnetization, the so-called functionally graded composites, show ME effects without an external magnetic bias field. Such ME sensors containing functionally graded ferromagnetic layers are denoted as self-biased sensors.

The ME sensors were clamped at one end and oriented with their longitudinal axis in a vertical orientation. An aluminum clip was used to attach a 34 gauge copper wire and a suspended weight from the free end of the cantilever. The length of the wire was varied from 4 to 20 cm long. The largest weight employed was 4 N. A set of Helmholtz coils, powered by an Agilent 33220A signal generator, applied a sinusoidal, time varying field along the longitudinal axis of the sensor. No flux concentrators were used. The signal was detected using a charge coupled amplifier, PCB Piezotronics Model 441A101, and then filtered in a SR640 low-pass filter with no gain before being sent to either a spectrum analyzer that uses a LabVIEW VI program or to a SR830 DSP lock-in amplifier. In either case, all signals were averaged for 60 s. Resonance frequencies for each cantilever setup were obtained by sweeping the frequency of a 0.0162 Oe external field at progressively finer intervals around a peak in the

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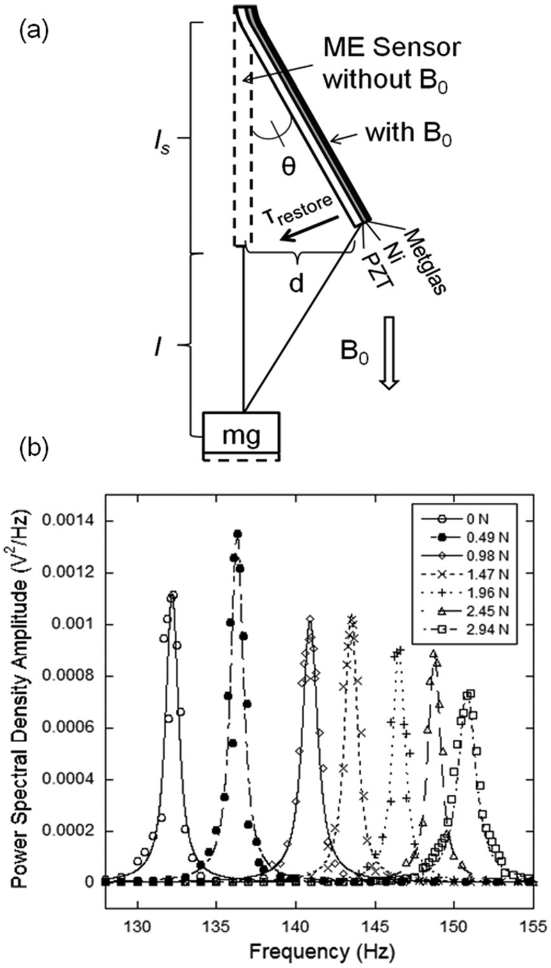

FIG. 1. (a) Diagram of the setup for an asymmetric ME sensor in which θ is the small angle away from the vertical direction. (b) Resonance peaks of sensor in an oscillating field of 0.0162 Oe with different in-plane tensile forces.

signal. All the measurements were conducted in our laboratory without the benefit of vibration isolation or magnetic, electric, and thermal shielding.

Consider the situation depicted in Fig. 1(a). We are using the bending mode in our experiments on the asymmetric ME sensor with the suspended weight. As the cantilever sensor bends, because of its inertia, it is unlikely that the suspended weight will move appreciably. Nevertheless, the suspended weight provides an additional restoring torque. If we assume a rigid beam pivoting about its suspension point, then this additional restoring torque τ_{ar} is given by

$$\tau_{restore} \cong mgd\left(1 + \frac{l_s}{l}\right), \tag{1}$$

where mg is the weight, d is the deflection of the free end of the sensor from the vertical direction, l_s is the length of the sensor, and l is the length of the wire. Based on Eq. (1), one sees that there are two ways to change this additional restoring torque. One can vary either the tensile force through the weight mg or the length of the wire l transferring this force. We have investigated both methods and found that either one can be used to increase the resonant frequency of asymmetric ME sensors.

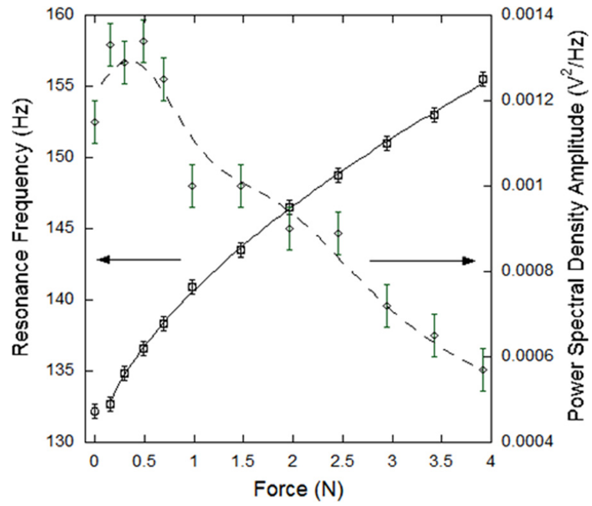

FIG. 2. (Color online) The change in resonance frequency and peak amplitude in the power spectrum at this frequency measured in an AC field of 0.0162 Oe as a function of the in-plane tensile force.

Figure 1(b) shows an increase in f_r as one increases the in-plane tensile force applied to the free end of the cantilever by adding weights to an attached wire of length 10.2 cm. The shift in resonance frequency is consistent with previous studies on cantilevers with axial loads.[16] The mechanical quality factor Q did not appreciably change for the range of forces in this study. Therefore, one observes, as expected for a larger restoring torque, that as the tensile force is increased above 2 N, the ME response is reduced, i.e., the amplitude of the peaks decreases. An interesting, unexpected result is that for small forces lower than 0.5 N, the amplitude of the resonance peak increases with increasing tensile force. This result was observed for two, similar, asymmetric ME sensors. The increase in amplitude is likely due to the Villari effect[17] induced by the added tensile force on the magnetic properties of the Metglas and/or Ni. The change in f_r and the amplitude of the signal at resonance as a function of the in-plane tensile force from the suspended weight is shown in Fig. 2.

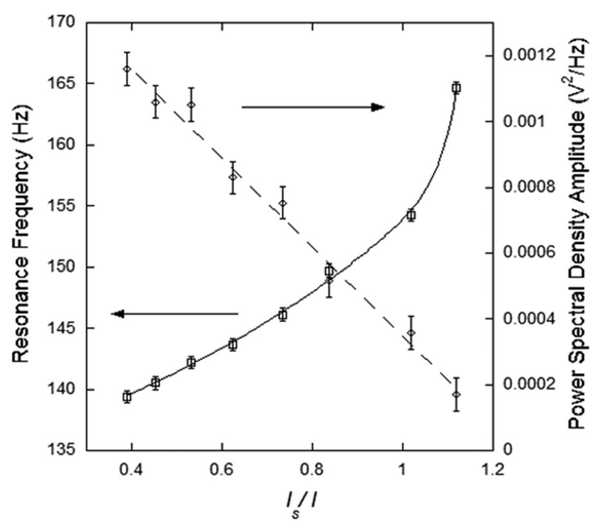

FIG. 3. The change in resonance frequency and peak amplitude in the power spectrum at this frequency measured in an AC field of 0.0162 Oe as a function of the inverse length l of the wire used to suspend the weight. The cantilever length l_s is 5 cm and tensile force is 1 N.

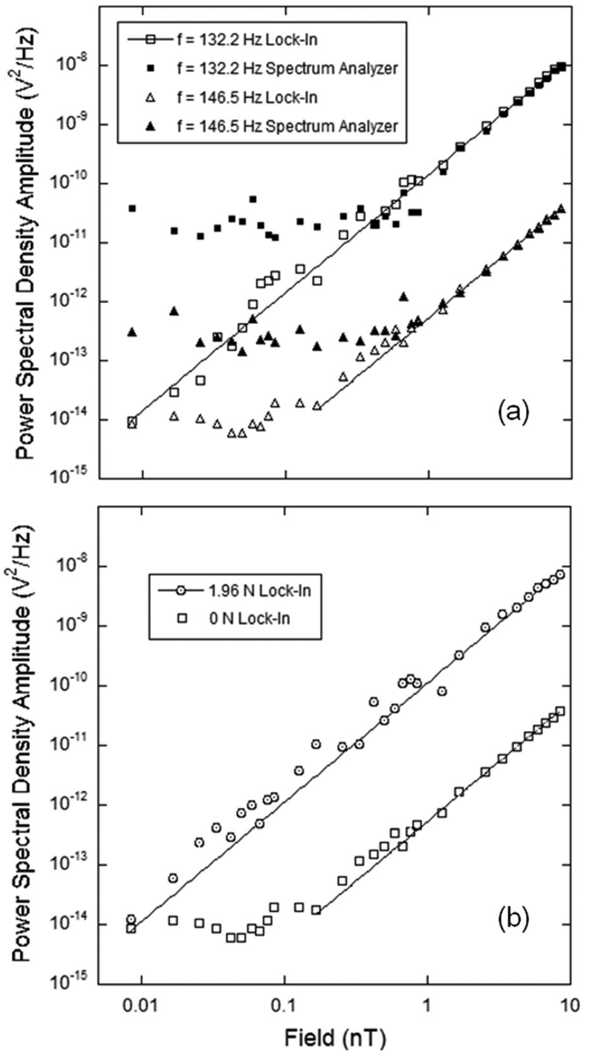

FIG. 4. (a) Signal vs. applied field at and above the unshifted resonant frequency of 132.2 Hz. The unfilled (filled) symbols denote the points from the spectrum analyzer with (without) using the lock-in amplifier. (b) Signal vs. applied field at the shifted resonant frequency $f_r = 146.5$ Hz and at the unshifted $f_r = 132.2$ Hz in the presence of a 1.96 N tensile force.

Results on changing f_r by varying the length l of the wire with a constant 1 N force are shown in Fig. 3. One sees that decreasing l also increases f_r, and that the curvature of the increase is different from that shown in Fig. 2. Since changing the wire length only increases the restoring torque and not the in-plane tensile force, the effect on the amplitude is more predictable. Thus, one does not have to consider possible Villari effects in designing ME devices where the wire length l is varied. However, in applying this concept to practical sensors, it is probably more straightforward to sweep f_r by changing the in-plane tensile force using a piezoelectric actuator rather than changing l.

Data are shown in Fig. 4(a) of the power spectrum amplitude for applied magnetic fields at and above the unshifted resonance of 132.2 Hz. Points from both the spectrum analyzer and lock-in amplifier are included; the data from the latter have been normalized so that these values coincide with those of the spectrum analyzer at high field. The gain in spectrum analyzer signal amplitude at resonance is largely negated by a similar increase in the background. However, by demodulating the signal using the lock-in amplifier at the signal frequency, we are able to decrease the background noise and detect fields at least ten times lower when operating at f_r than when operating above it. In Fig. 4(b), similar results are presented for the case f_r is shifted to 146.5 Hz by adding a 1.96 N weight. One sees the important result that the increased sensitivity at f_r is maintained when f_r is increased by applying an in-plane tensile force. The tuned ME sensor can detect signals lower than 10 pT at the shifted value of f_r. Still better sensitivity may be achieved if we can understand and decrease the background around f_r.

In summary, we have demonstrated a technique to tune the resonant frequency of asymmetric ME sensors. Based on the simple principle of adding a restoring torque, we have developed two related paths for high sensitivity detection or monitoring of sources with varying output frequency. We have been able to shift f_r of a self-biased asymmetric sensor by 20% from its intrinsic resonance of 132.2 Hz while retaining the order of magnitude increase in sensitivity at resonance. This allows the detection of a 10 pT signal at both the shifted and unshifted f_r in an unshielded environment. There are almost no other low cost magnetic sensors with this performance. The approach can be applied to non-magnetic, mechanical systems, with the potential to continuously sweep f_r by using a piezoelectric actuator.

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